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14. ABSTRACT
This paper presents field measurements of turbulence from the Skaneateles Optical Turbulence Exercise (SOTEX, July 2010), during which images of a target were collected over a 5 m path length at various depths in the water column, concurrent with profiles of the turbulent strength, optical properties, temperature, and conductivity. Turbulence was characterized by the turbulent kinetic energy dissipation (TKED) and thermal dissipation (TD) rates, which were obtained in close proximity using both a Rockland Scientific Vertical Microstructure Profiler (VMP) and a Nortek Vector velocimeter in combination with a PME CT sensor.

15. SUBJECT TERMS
turbulence, underwater imaging, dissipation rate, microstructure, acoustic doppler velocimeter

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Measurements of turbulence for quantifying the impact of turbulence on underwater imaging

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Abstract— **It has long been acknowledged that turbulence affects propagation of light in the ocean. Physically, this is because turbulent inhomogeneities of the flow are associated with fluctuations in temperature and salinity. Variations in these passive scalars alter the water density, inducing variations in the refractive index, which result in near-forward scattering from turbulent inhomogeneities. In applications such as underwater imaging, the near-forward scattering from turbulence becomes a limiting factor over longer ranges and under conditions of stronger turbulence. The magnitude of this degrading effect depends upon the underwater environment, and can rapidly degrade the quality of underwater imaging under certain conditions. Overcoming this degradation through enhancement of imaging systems and post processing is important for such applications as diving, navigation, robotics, communication and target and mine detection and identification. To investigate the impact of turbulence upon underwater imaging and to compare with our previously developed model, quantified observation of the image degradation concurrent with characterization of the turbulent flow is necessary, spanning a variety of turbulent strengths. Therefore, we present field measurements of turbulence from the Skaneateles Optical Turbulence Exercise (SOTEX, July 2010), during which images of a target were collected over a 5 m path length at various depths in the water column, concurrent with profiles of the turbulent strength, optical properties, temperature, and conductivity. Turbulence was characterized by the turbulent kinetic energy dissipation (TKED) and thermal dissipation (TD) rates, which were obtained in close proximity using both a Rockland Scientific Vertical Microstructure Profiler (VMP) and a Nortek Vector velocimeter in combination with a PME CT sensor.' While the two instrumental setups demonstrate reasonable agreement, some irregularities highlight the difficulties of accurately quantifying the desired parameters, which are likely associated with the spatial and temporal variability of the turbulence field. Supplementary measurements with the Vector/CT in a controlled laboratory convective tank will shed additional light on the quantitative relationship between image degradation and turbulence strength.**

Keywords-turbulence, underwater imaging, dissipation rate, microstructure, acoustic doppler velocimeter

I. Introduction

The capability to see farther underwater is of interest in many different fields, particularly in the field of underwater imaging. This capability is highly desirable for recreational, scientific, and military applications such as diver visibility, navigation, robotics, archeology, marine research, underwater photography, and target and mine detection and classification. In order to enhance underwater imaging, an understanding of the physics involved in light propagation underwater is necessary. As the light propagates through the water column, scattering degrades the quality of the image. Scattering may be attributed to a combination of scattering from the water itself, particulates suspended in the water column, or turbulence present along the propagation path. The magnitude of this degrading effect depends upon the underwater environment, and can rapidly degrade the quality of underwater imaging under certain conditions. While scattering from particulates contributes more significantly to image degradation in general, especially at larger viewing angles, under conditions of strong turbulence, as is found near the surface, mixed layer, and bottom of the water column, near-forward turbulent scattering produces a significant contribution [1, 2].

Although much work has been done to quantize and overcome the effects of particulate scattering [3-5], the problem of turbulent scattering has only become a source of investigation more recently [6]. Thus, the work presented here is part of an effort aiming to quantize the effect of turbulent scattering on underwater imaging. Such quantization will not only allow for improved understanding of the physics contributing to the degradation of underwater imaging, but will also provide opportunity for overcoming such degradation and opening the door to opportunities for enhancing imaging techniques. This effort will also provide insight into optical techniques for characterizing turbulent flow in the water column. As a part of this larger effort, the present paper details the turbulence measurements associated with a field experiment used to image underwater and simultaneously measure the turbulent strength over which the images were obtained.

II. Background

Turbulence affects light propagation underwater because the slight changes in index of refraction associated with fluctuations in temperature or salinity refract the light as it passes through the turbulent layer, effectively inducing multiple scattering in the light beam [7-10]. Under conditions of weak turbulence, however, this effect is negligible, and scattering by particulates dominates. As the turbulence grows

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stronger, the fluctuations in refractive index become more frequent, and the scattering due to turbulence becomes significant [10]. Effectively, this phenomenon is akin to the observed twinkling of a star or the effect produced from heat rising from a hot surface. In regions of strong turbulence, this effect is significant enough to affect optical communications, diver visibility, and underwater imaging.

Methods have been developed to compensate for the effects of particulate scattering upon underwater imaging by correcting underwater images with the point spread function (PSF) response, which describes how light interacts with the water for the current environmental conditions [3, 4]. These methods are more complicated for scattering from turbulence, however, due to the rapid temporal and spatial variation of the turbulent field, even within the field of view of the sensor. Thus, turbulence presents a more difficult problem in post-processing of images to correct for turbulent scattering, at least until quantification of the relationship between image degradation and turbulent strength is determined. In theory, however, the degrading effects of scattering from turbulence may be corrected in a similar manner to that of particulates, if the turbulence can be characterized by its turbulent kinetic energy dissipation (TKED) and thermal dissipation (TD) rates, so as to yield the associated point spread function [6]. This work will therefore detail the turbulence measurements associated with an effort to quantify the effects of turbulence upon underwater imaging degradation. In particular, the turbulence will be characterized by the turbulent kinetic energy (TKED) rate. The TKED rate is an indication of the diffusivity of momentum of the flow, thus providing a measure of how quickly a velocity disturbance within the flow will be dissipated, which will be estimated from measurements of the microstructure and velocity fluctuations of the water column.

III. Measurements

A. Measurement Conditions

Measurements were carried out as part of the Skaneateles Optical Turbulence EXercise (SOTEX), conducted on Lake Skaneateles, New York in July 2010. Images were collected over a 5 m path length at various depths within the water column, and at different sites on the lake. Fig. 1 shows the approximate location of the two stations, the first (S1, red circle) near the center of the lake (42.8668° N, 76.3920° W) over a sloping bottom with an approximate depth of 70 m, the second (S2, blue triangle) at the northern end of the lake (42.9063° N, 76.4058° W) over a flatter bottom with an approximate depth of 50 m. Skaneateles was chosen for this exercise on account of its well-known optically clean waters, having the highest clarity of any of the Finger Lakes, with an average secchi depth near 8 m [11], thus allowing for imaging under varied turbulent strength, but with little scattering contribution from particulates. July was chosen for this exercise to ensure a well-defined thermocline (as demonstrated by the temperature profiles shown in Fig. 2) and strongest possible conditions for optical turbulence in the lake.

Turbulence measurements were obtained from both a Vertical Microstructure Profiler (VMP) and a Vector Velocimeter combined with a Conductivity and Temperature sensor (Vector/CT). For deployment on the first day (July 27th), the Vector/CT was deployed on the optics package, with the VMP deployed from a separate vessel, as depicted in Fig. 3(a). While the Vector/CT profile consisted of pauses at particular depths for acquiring a time series of velocities that would be used for turbulence calculations, the VMP profiled continuously. For all subsequent days, the Vector/CT was deployed upon the IMAST (Image Measurement Assembly for Subsurface Turbulence), the 5 m long rigid structure used for acquiring images. The IMAST was deployed both vertically and horizontally, as depicted in Fig. 3(b), both during the day with a passive imaging target and at night with an active target, and also profiled the water column in a step fashion, pausing at each depth for a given period of time to acquire images and velocity time series at a given depth. The VMP was deployed from a separate vessel in close proximity, and profiled continuously during the IMAST deployment. Complementary profiles of the water column optical properties were also obtained with a WETLab ac-9, bb sensor, CTD, and a Sequoia Scientific Laser In-Situ Scattering Transmissometer (LISST).

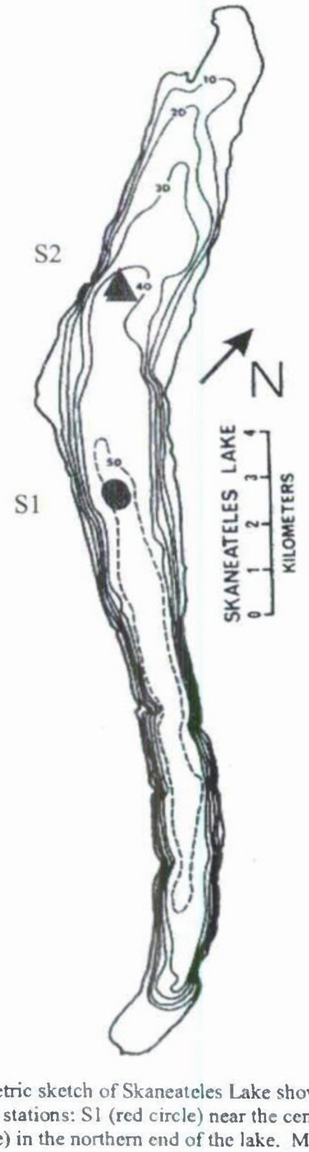

Figure 1. Bathymetric sketch of Skaneateles Lake showing the approximate location of the two stations: S1 (red circle) near the center of the lake, and S2 (blue triangle) in the northern end of the lake. Map adapted from http://www.ourlake.org/html.

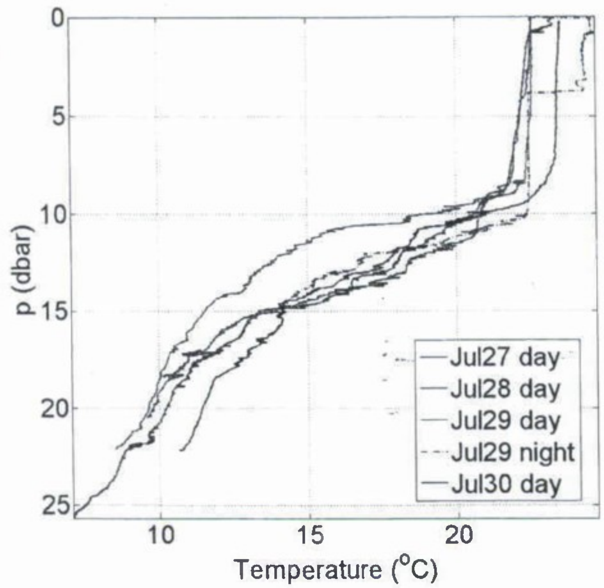

Figure 2. Temperature profiles (°C) corresponding to the dissipation profiles shown in Fig. 4 for deployments on July 27 day (solid red), July 28 day (solid green), July 29 day (solid blue), July 29 night (dashed purple), July 30 day (solid black). All profiles are from S1 except for the July 29th daytime deployment, which is from S2. Depth is indicated by pressure (dbar).

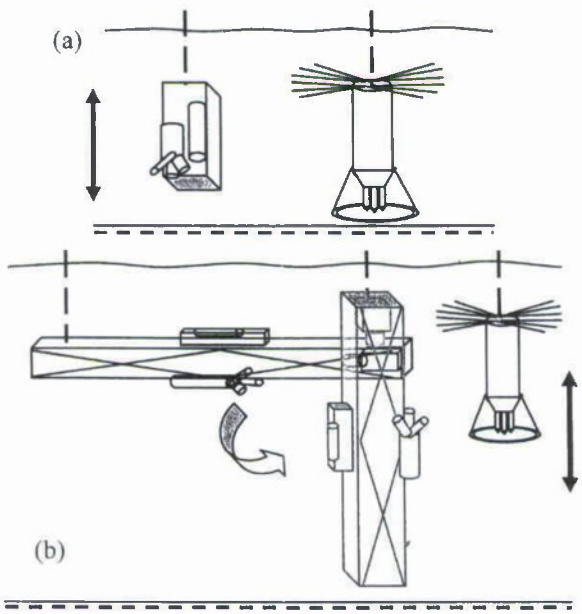

Figure 3. Diagram of deployment setup showing alternate deployment configurations: (a) Vector/CT deployed vertically on optics package, and (b) Vector/CT deployed on IMAST both vertically and horizontally. Note, in both instances, the VMP was deployed from a separate vessel.

B. *Vector/CT Turbulence Measurements and Calculations*

The Vector/CT instrumental setup consists of a Nortek Vector acoustic doppler 3D velocimeter and a Precision Measurements Engineering (PME) fast Conductivity and Temperature (CT) sensor. The two instruments are mounted near the center of the IMAST structure, and the heads of the instruments placed in such a way as to sample the same volume of water, thus providing time series of the 3D velocity, temperature, and conductivity fluctuations of the sample water volume. As the instrument is commonly used for laboratory measurements or stationary moorings, the instrument requires collection of a time series of velocities at a stationary depth in order to compute the turbulent dissipation rates. Therefore, during deployment, the IMAST profiled the water column by pausing at each depth for five to ten minutes to capture the turbulence statistics. Since the instrument was deployed from a vessel and not a stationary platform, the influence of the surface movement of the vessel was evident on the velocity spectra, however it did not affect dissipation estimates since its spectral signature was outside the inertial subrange used for calculations. Measurements were collected at a rate of 32 Hz to allow for adequate sampling of turbulent fluctuations.

For characterizing the turbulent flow, the TKED rate, ε, is calculated from the Vector velocity measurements. Since the velocity spectra conform to a -5/3 slope over a wide frequency range, the energy spectra relations used under the condition of local isotropy are applicable assuming Kolmogorov's theory, and the TKED rate is determined from

$$\varepsilon = \left[\frac{1}{C\alpha} k^{5/3} S(k) \right]^{3/2} \tag{1}$$

by fitting a line with a -5/3 slope to the inertial subrange of the velocity spectra. Here, k is the wavenumber, S the velocity spectral density, and C and α are constants given by 18/55 and 1.5, as determined from the isotropic relations and experimental results, respectively [12].

C. *VMP Turbulence Measurements and Calculations*

Microstructure observations for SOTEX were collected by a specialized instrument, a vertical microstructure profiler (VMP), designed and produced by Rockland Scientific International, Canada. The VMP profiler is designed to measure dissipation-scale turbulence in oceans and lakes up to 500 m. It is equipped with four microstructure sensors: two shear sensor probes, one thermistor (FP07), and micro-conductivity (SBE7). These sensors allow measuring with high accuracy and resolution microscale velocity shear, temperature, and conductivity, with a shear sampling rate of 512 Hz. Additionally, the VMP profiler has externally attached SeaBird SBE7-3F temperature and SBE-4C conductivity sensors. The profiler also measures pressure. During the SOTEX experiment, over 100 VMP drop profiles were executed, with drop velocities between 60 and 90 cm/s. All drops returned high-quality data that later were used to estimate turbulent energy (shear data) and temperature (thermistor data) dissipation rates.

The turbulent energy dissipation rate, ε, was computed by integrating the shear spectrum from k_1 to k_2 using the isotropic formula:

$$\varepsilon = \frac{15}{2} \nu \int_{k_1}^{k_2} \psi(k) dk \tag{2}$$

where k is the wavenumber, ν is the kinematic molecular viscosity of water, and ψ(k) is the shear spectrum. Spectra of the velocity shear were calculated from consecutive segments of 1024 data points, corresponding to a bin height of approximately 0.8 m, with an overlap between adjacent bins of 512 points. The lowest wavenumber $k_1$was set to 1 cpm, and the highest one (k_2) was set to the wavenumber where the shear spectrum has a minimum between the natural spectrum and a high wavenumber peak, but not higher than 30 cpm.

IV. RESULTS

From the relations given in the previous section, turbulent energy dissipation rates were determined from both the Vector Velocimeter and the VMP. While both instruments here provide results of turbulent dissipation in the form of profiles through the water column, it should be kept in mind that the VMP profiles continuously in order to provide dissipation estimates from the shear spectra, while the Vector/CT pauses at a given depth in order to provide dissipation estimates from the velocity spectra at that depth. Comparisons of the dissipation rates for varying deployments are presented in Fig. 4, where the Vector/CT measurements are plotted as open circles, and the VMP measurements are plotted as closed dots. The results plotted in Fig. 4(d) were collected during the nighttime, but all other results are from daytime measurements. Similarly, the results in (c) were collected from station S2, but all other results are from S1. And finally, all results are from deployment of the Vector/CT mounted inside the IMAST except for (a), when it was deployed on the outside of the optics package.

All profiles generally demonstrate the heightened turbulent kinetic energy dissipation rate near the surface and mixed layer, with decreasing dissipation at depth (no profiles extended to the lake bottom, where higher dissipation rates would also be expected). No measurements were made directly beneath the surface due to instrument deployment limitations, but begin at a depth of about 5 m, and extend to depths of 40 to 50 m for the VMP, 15 to 25 m for the Vector/CT.

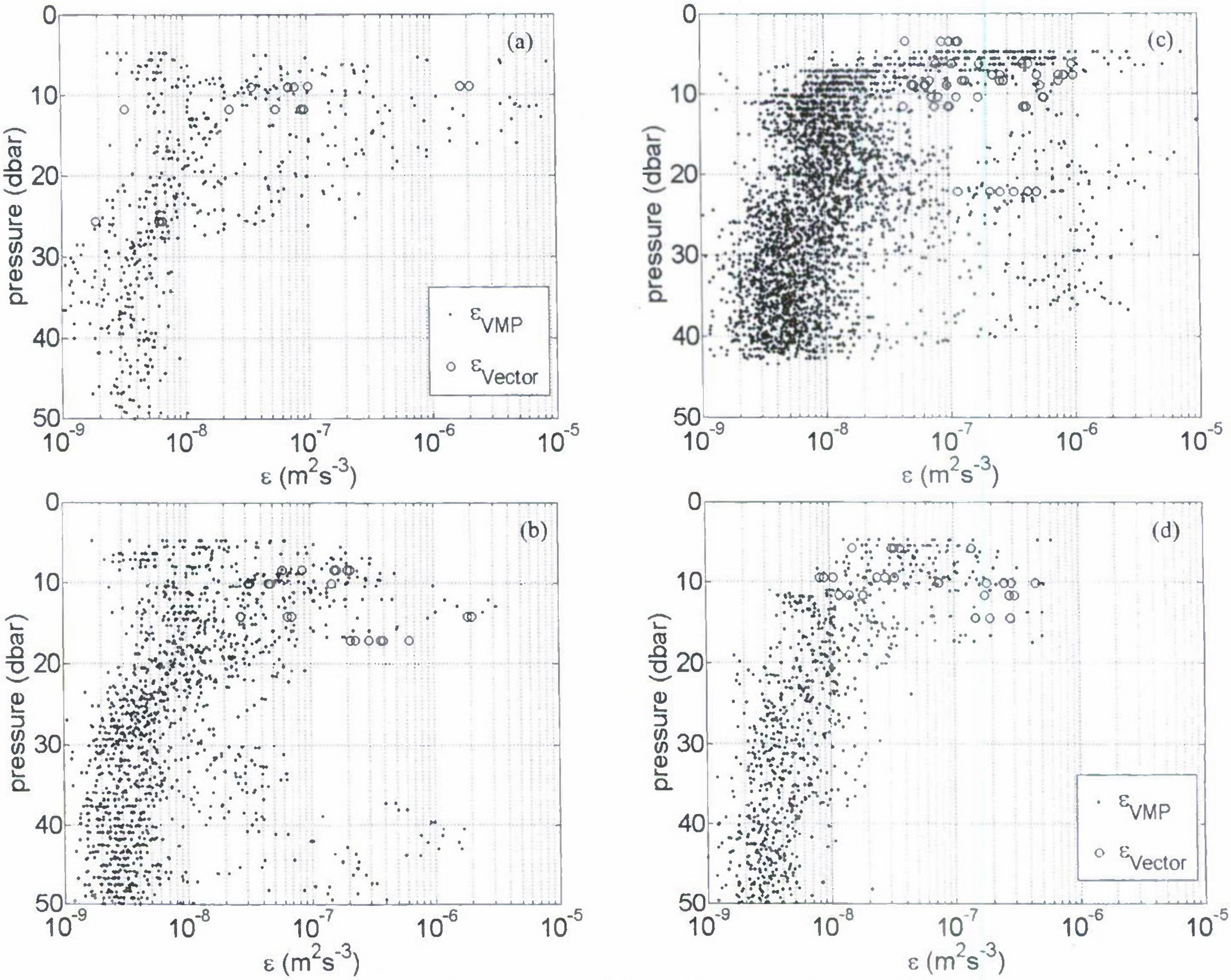

Figure 4. Profiles of turbulent kinetic energy dissipation rates, ε (m^2s^{-3}) for several deployments determined from VMP (dot) and Vector (open circle) measurements: (a) July 27 daytime at S1, (b) July 28 daytime at S1, (c) July 29 daytime at S2, (d) July 29 nighttime at S1. The corresponding temperature profiles for each station are shown in Fig. 2. Note that in all cases the Vector/CT was on the IMAST except for (a), when it was on the optics package. Depth is given by pressure (dbar).

The two instrumental setups demonstrate reasonable agreement, with those of the Vector/CT tending to be higher in general than those of the VMP, as expected given the nature of the instrument setups, sampling rates, and estimate methods. Some deployment profiles demonstrate irregularities, however, highlighting the spatial and temporal variability of the turbulence field, and the difficulties this variability induces in quantifying the desired parameters. In Fig. 4(a), for example, dissipation rates of both instruments span a wide range of values. The wide range of values is likely due to the significant drift experienced by both deployment vessels over the course of the deployment, showing the spatial and temporal changes in turbulent dissipation. However, the two vessels maintained close proximity of 5 to 10 m despite the drift, thus estimates from both instruments span the same range for most depths. Although the vessels drifted less during the deployment shown in (b), proximity between the vessels was difficult to maintain, and separation was on the order of 50 to 100 m, which could account for the rather high estimates from the Vector/CT in comparison to the VMP, demonstrating the spatial variation in the turbulence field. Closer proximity of the two vessels (25 to 50 m) was maintained for the measurements shown in (c) and (d), although the vessels maintained a greater separation than on the first day shown in (a), and there was again significant drift during the course of the deployment for (c). Additional causes of the discrepancy between measurements could be attributed to the mounting of the Vector/CT within the IMAST structure for deployments (c) through (d), since it was mounted outside the optics cage in (a).

V. Conclusions

Motivated by efforts to assess the impact of turbulence on underwater imaging, the Skaneateles Optical Turbulence EXercise (SOTEX) provided a unique opportunity to compare turbulent characterization measurements from two rather different instruments: the Vector acoustic doppler velocimeter and the Vertical Microstructure Profiler. Although the Vector is often deployed in a stationary moored setup, and the VMP in profile form, the two instruments demonstrated somewhat reasonable agreement in turbulent kinetic energy dissipation rate trend estimates when the two were deployed in close proximity. While some of the disagreement between instruments can be attributed to proximity and drift of the deployment vessels, a better comparison could be made if these factors were eliminated. Such a deployment is difficult, however, due to the deployment needs of each instrument. Future work will further examine the agreement between the VMP and the Vector/CT through comparison of their estimated turbulent temperature dissipation rates.

Acknowledgment

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